Hemodynamics Induced after Acute Reduction of Proximal Thoracic Aorta Compliance

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Objective: to investigate the affect of reduced aortic compliance on cardiovascular hemodynamics.

Materials and Method: fourteen Yucatan miniature swine were divided into two equal groups, a Sham Operated Group and a Banding Group. A Teflon prosthesis was wrapped around the aortic arc in order to limit proximal aortic compliance (Banding Group). Data were recorded operatively (after implantation of a pressure sensor and a flow probe in the ascending aorta), after banding (only in the Banding Group) and at 2 days postoperatively.

Results: after banding, compliance decreased by 52 ± 13% (X ± SEM) (p < 0.01) while systolic and pulse pressure increased by 37 ± 8% (p < 0.05) and 87 ± 31% (p < 0.01), respectively. Diastolic pressure, mean blood pressure, cardiac output and systemic vascular resistance did not change significantly. Aortic characteristic impedance increased nearly 2.5 times. Amplitudes of forward and reflected pressure waves (derived from the aortic pressure wave) increased by 96 ± 41% and 174 ± 46%, respectively (p < 0.05), while the time delay between the two decreased by 36 ± 7% (p < 0.05).

Conclusions: about half of the total arterial compliance is located in the proximal thoracic aorta. Arterial reconstruction of the proximal aorta with a non-compliant graft results in a significant decrease in systemic arterial compliance, which in turn increases systolic and pulse pressure. The development of more compliant prosthesis, which matches the host artery compliance, is expected to reduce the hemodynamic changes induced after their implantation.

Key Words: Arterial compliance; Arterial impedance; Hypertension; Vascular prosthesis; Synthetic grafts; Compliance mismatch.

Introduction

The natural aorta and especially the aortic root, is a compliant vessel, which expands as pressure increases during systole, to be released later during diastole. Ejection of the blood from the left ventricle is possible because the volume of the large arteries is able to increase in order to accommodate the ejected blood. This function is described as the “Windkessel property” of the aorta and the major conduit arteries and results in a considerable damping of the pressure wave and a significant reduction of cardiac afterload, enabling the heart to work efficiently near the optimum point on the Starling curve.

Operation on the diseased or damaged aorta is performed mainly using synthetic grafts. Conventional vascular prostheses, such as woven Dacron, do not distend as the stroke volume ejected by the heart enters its lumen. Therefore, the use of these non-compliant grafts leads to a decrease in systemic arterial compliance. Furthermore, the introduction of an inelastic graft in the highly distensible natural aorta may change the performance of the cardiovascular system due to the compliance mismatch between the host artery and the prosthesis.

Vascular prostheses feature mechanical properties that are very different from those of natural arteries. After the insertion of a non-compliant graft, two main consequences appear. First, at the interfaces, the different propagation rate of pressure waves, dependant on wall elasticity, causes wave reflections and eddy currents. These in turn have been
shown to promote thrombi formation or intimal hyperplasia. Second, due to the different radial dilation of the prosthesis and the host vessel, over-stresses arise in the sutures at the anastomoses which in turn lead to fatigue failure of sutures, tearing of the host artery resulting in anastomotic aneurysm formation.

Clinical observations have documented left ventricle hypertrophy after ascending-abdominal aorta bypass for thoracoabdominal aneurysm, most likely a result of increasing aortic input impedance. Later reports correlated left ventricle hypertrophy seen after proximal or long bypass procedures, with non-compliant grafts, with increased characteristic impedance, decreased Windkessel effect of the proximal aorta and increased systolic wall stress. This “stiffening” of the vasculature has been shown to augment cardiac dysfunction and ischemia due to coronary occlusion by tightening the link between cardiac systolic performance and myocardial perfusion.

From a hemodynamical standpoint, loss in aortic compliance means increase in aortic characteristic impedance and increase in the pulse wave velocity, which is the speed with which pressure waves travel in the aorta. The increase in aortic characteristic impedance means that for a given cardiac output the early systolic pressure wave will be augmented due to increased aortic stiffness, and this contributes to increased systolic pressure. The increase in pulse wave velocity means that pressure waves travel faster in the aorta and thus the reflected pressure waves traveling from the periphery towards the aorta will arrive in the aorta earlier, during the systolic phase, further augmenting systolic pressure. Simulations of a replacement of the ascending and descending aorta with a stiff prosthesis using a distributed model of a standard human arterial tree have supported, in a qualitative sense, the above stipulations: when the aorta is replaced with a relatively stiff tube yielding a 90% increase in characteristic impedance total arterial compliance decreased by 30%, pulse pressure increased by 46% local pulse wave velocity increased by 109%.

This experimental study was undertaken to investigate the effect of reduced proximal aortic compliance, such as after proximal aortic reconstruction, on cardiovascular hemodynamics. This article supplements and expands previous reports by not only studying results from acute open or closed chest animals but also studying the results of closed chest animals 2 days after surgery. Furthermore, we have performed compliance reduction in a manner that preserves the natural geometry of the arterial tree.

Materials and Method

Surgical instrumentation

Fourteen Yucatan miniature swine of either sex weighing 22–30 kg, after being fasted overnight, were pre-medicated [midazolam (0.4 mg/kg) and azaperone (5 mg/kg)] and then intubated under general anesthesia [inhaled isoflurane, i.v. fentanyl (5 μg/kg/h), i.v. pancuronium (0.2 mg/kg)] and the lungs mechanically ventilated with 40% O₂ in air (Siemens ventilator, model Servo 900B, Elema, Sweden). The body temperature was maintained at 37–38°C with a warm air fan as well as with humidified and heated respiratory gases. Blood temperature, respiratory gases (O₂, CO₂, isoflurane) (Datex Ultima™, Datex Instrumentarium, Helsinki, Finland) and pulse oxymetry (Nellcor N2500, Pleasanton, CA, U.S.A.) were continuously monitored.

The left thorax was prepared with chlorhexidine, 70% isopropyl alcohol, and iodine solution. After a left thoracotomy through the fourth intercostal space followed by pericardiotomy, the heart and great vessels were exposed and the aortic arc was carefully dissected free from the surrounding connective and fatty tissue. A calibrated pressure transducer (Konigsberg Instruments Inc, Pasadena, CA, U.S.A.) was implanted in the ascending aorta 0.5 cm above the coronary arteries to obtain aortic pressure measurements. An appropriately sized transit-time ultrasonic flow probe (Transonic System Inc., Ithaca, NY, U.S.A.) was placed around the ascending aorta for aortic blood flow measurement just above the aortic pressure transducer (Fig. 1). Both the pressure sensor and the flow probe were fixed in place in order to be used for the entire length of the experiment. All instrumentation cables were exteriorized through the 6th intercostal space, fixed on the back of the animal and were routed to a computer data processor where a recording was made as a control condition (reported as “after instrumentation”). All signals were digitized, treated and further analyzed with IOX 1568 laboratory analysis program (EMKA Technologies, Paris, France).

The 14 miniature swine were divided into two equal groups, a Sham Operated Group (Control Group) and a Banding Group. Both groups underwent the same surgical instrumentation procedure (described above). In the Banding Group the ascending, transverse and the beginning of the descending aorta were banded using a Teflon prosthesis (procedure described below).

Baro-receptors located in the wall of the aortic arc may be affected after exposure of the aortic arc. To balance this probable effect, the animals in the control group underwent the same extensive exposure of the
aortic arc as the animals in the Banding Group. Furthermore, the presence of an intact autonomic reflux was intra-operatively assessed by testing for the presence of heart rate response to varying preload pressures after temporarily occluding and releasing the inferior vena cava.

Banding procedure

In order to experimentally simulate acute proximal aortic stiffness, three strips of Teflon were placed around the aortic arc (Fig. 1). One strip was placed around the ascending aorta, between the flow probe and the innominate artery (approximately 1 cm wide), a second strip (0.6–0.8 cm) between the innominate and the left subclavian artery (pigs have only two branches arising from the aortic arc) and a third strip, approximately 1.3 cm, around the proximal descending aorta. The strips of Teflon were placed snugly around the aorta, adjusted tight enough to not allow the aorta to expand during systole but without causing a stenosis, and sutured into place. The amount of pressure applied around the banding was empirically estimated intra-operatively, where; the bands were placed tight enough around the aorta as to retain pulsatile movement of the aortic wall, but lose enough to allow a closed dissector clamp to freely pass between the aortic wall and the bands. In order to verify that the banding did not cause a stenosis, a pressure reading was taken from the descending aorta, after the banding, by temporarily introducing a calibrated intravascular needle-catheter into the aorta and comparing the pressure curve to the aortic pressure curve taken from the Konigsberg pressure sensor. After verification was obtained (absence of a pressure gradient) a data recording was made (described as “after banding – acutely” in the graphs that follow).

On the second post-operative day the animals were anesthetized and mechanically ventilated similarly to the day of operation and another set of data recordings was conducted.

The experimental protocol was approved by the University of Geneva animal ethics committee as well as by the cantonal veterinary office and conforms with the “Guide for the Care and Use of Laboratory Animals by the US National Institutes of Health” (NIH Publication No. 85-23, revised 1996).

Data analysis

For the sham-operated group, data were recorded directly after instrumentation and on the 2nd post-operative day. For the banded animal group, measurements were done directly after instrumentation but before banding (situation identical to the sham group), after banding and on the 2nd post-operative day.

Hemodynamical and arterial parameters

Arterial blood pressure and flow were directly measured by the implanted pressure transducer and flow probe. These readings were relayed to the computer..
where the IOX software program registered the measurements to the data bank with a sampling frequency of 500 Hz. Using the blood pressure and flow inputs, the software calculated and registered the heart rate, pulse pressure, systolic pressure, diastolic pressure and mean blood pressure from the pressure input signal and the stroke volume, the maximum flow, minimum flow and mean flow, and the cardiac output from the flow input signal. All parameters of each animal were calculated for 10–15 consecutive heartbeats, to obtain an average value.

Total arterial compliance \(C\) was estimated using the pulse pressure method.\(^{13}\) Peripheral resistance \(R\) was calculated as mean aortic pressure over mean flow but can also be represented by the impedance modulus at zero frequency.\(^{14}\)

Aortic characteristic impedance \(Z_c\), which is inversely related to the wall distensibility of the proximal aorta and is a measure of all the factors which in the absence of wave reflections combine to limit pulsatile flow,\(^{15}\) was expressed as the average of the modulus of the input impedance in the frequency range between 3 and 10 Hz.

**Analysis of wave reflections**

To assess the contribution of wave reflections on the arterial hemodynamics, in control conditions and after banding, we separated the aortic wave into its forward and backward (reflected) wave components as proposed by Westerhof et al.\(^{16}\)

\[
P_f = \frac{P + Z_c Q}{2} \quad \text{and} \quad P_b = \frac{P - Z_c Q}{2}
\]

where \(P_f\) and \(P_b\) are the forward and backward wave components of the aortic pressure wave, respectively, and \(Q\) is aortic flow. We analyzed the amplitude of the forward and backward wave components as well as the timing of their peaks.

**Statistical analysis**

Grouped data are presented as means ± SEM. In the Sham Operated Group we report the mean values during instrumentation and on the 2nd post-operative day. In the Banding Group we report the mean values pre- and post-banding during operation as well as on the 2nd post-operative day. Unpaired student’s \(t\)-tests were used for statistical comparison of the sham-operated animals to the animals in the banded group. Paired \(t\)-tests were used for statistical comparison of the changes in hemodynamic parameters before and after banding in the banded group. Only \(p\)-values less than 0.05 were considered significant.

**Results**

The decrease in total arterial compliance, after banding, caused changes in the morphology of the pressure curves that resulted in an increased pulse pressure amplitude (Fig. 2) and a partial loss of the aortic “Windkessel” function. Immediately following banding, systolic aortic pressure increased significantly and increased even further in the post-operative period. Following banding, the shape of the pressure wave is characterized by a late systolic increase. On the contrary, flow was unaltered after banding.

**Hemodynamical parameters**

Comparison of mean values of all hemodynamic parameters during instrumentation and post-operatively for the sham group showed no statistical differences. This confirms that hemodynamics were not altered during the short-term post-operative period in this group (Table 1). Comparison between the sham operated animals and the banded animal group before banding also showed no statistical differences in all hemodynamic parameters.

Banding increased systolic pressure from 87 ± 5 to 101 ± 7 mmHg acutely and to 120 ± 5 mmHg on the 2nd post-operative day (\(p < 0.001\)) (Table 1). Diastolic pressure remained approximately the same (\(p = 0.19\)).

Pulse pressure increased from 23.8 ± 2.5 mmHg pre-banding to 42.3 ± 4.6 mmHg (\(p = 0.001\)) immediately following banding and to 44.4 ± 4.4 mmHg at 2 days post-operatively (\(p = 0.002\)). Banding did not change mean pressure and heart rate acutely, but at 2 days post-operatively both mean pressure and heart rate rose to 95 ± 7 mmHg and 116 ± 9 beats/min from 75 ± 5 mmHg and 91 ± 6 beats/min before banding, respectively (mean pressure: \(p < 0.05\); heart rate: \(p < 0.05\)). Cardiac output remained unchanged after banding ranging from 2.1 L/min before banding to 2.4 L/min on the 2nd post-operative day (\(p = 0.38\)).

**Arterial parameters**

Arterial compliance, characteristic impedance and peripheral resistance in the sham operated animals remained constant after instrumentation till the 2nd
Hemodynamics Induced after Compliance Reduction

![Graph showing changes in aortic blood pressure and flow before and after banding.](image)

Fig. 2. Typical recordings of aortic pressure and flow performed in one animal, before and after banding as well as on the 2nd post-operative day after banding. A significant increase in pulse pressure and a rise in systolic pressure is observed after banding, which is maintained post-operatively. Following banding, the shape of the pressure wave is characterized by a late systolic increase. Flow is not significantly altered after banding. (Note: Flattening in the before banding aortic pressure curve is due to the use of a common scale in the pressure axis.)

Table 1. Hemodynamic and arterial parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Animal group</th>
<th>After instrumentation</th>
<th>After banding (acutely)</th>
<th>2nd Post-op day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic blood pressure (mmHg)</td>
<td>Sham</td>
<td>85.3 ± 4.8</td>
<td>–</td>
<td>99.2 ± 5.3†</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>87.2 ± 4.9</td>
<td>100.8 ± 7.4</td>
<td>119.5 ± 5.2‡</td>
</tr>
<tr>
<td>Diastolic blood pressure (mmHg)</td>
<td>Sham</td>
<td>64.2 ± 5.2</td>
<td>–</td>
<td>74.3 ± 3.9</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>63.4 ± 4.3</td>
<td>58.6 ± 5.8</td>
<td>75.0 ± 7.1</td>
</tr>
<tr>
<td>Mean blood pressure (mmHg)</td>
<td>Sham</td>
<td>75.2 ± 4.6</td>
<td>–</td>
<td>88.0 ± 4.6</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>75.2 ± 4.7</td>
<td>76.9 ± 7.3</td>
<td>95.1 ± 6.6†</td>
</tr>
<tr>
<td>Pulse pressure (mmHg)</td>
<td>Sham</td>
<td>21.4 ± 1.5</td>
<td>–</td>
<td>24.9 ± 2.3</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>23.8 ± 2.5</td>
<td>42.3 ± 4.6</td>
<td>44.4 ± 4.4†</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>Sham</td>
<td>103 ± 11</td>
<td>–</td>
<td>110 ± 4</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>91 ± 6</td>
<td>92 ± 12</td>
<td>116 ± 9</td>
</tr>
<tr>
<td>Stroke volume (l/beat)</td>
<td>Sham</td>
<td>0.02 ± 0.005</td>
<td>–</td>
<td>0.02 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>0.024 ± 0.003</td>
<td>0.019 ± 0.002</td>
<td>0.021 ± 0.002</td>
</tr>
<tr>
<td>Cardiac output (l/min)</td>
<td>Sham</td>
<td>2.1 ± 0.3</td>
<td>–</td>
<td>2.4 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>2.1 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>2.4 ± 0.3</td>
</tr>
<tr>
<td>Compliance (ml/mmHg)</td>
<td>Sham</td>
<td>0.54 ± 0.04</td>
<td>–</td>
<td>0.51 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>0.53 ± 0.05</td>
<td>0.18 ± 0.03</td>
<td>0.27 ± 0.03‡</td>
</tr>
<tr>
<td>Zc (ml·mmHg⁻¹·s⁻¹)</td>
<td>Sham</td>
<td>0.21 ± 0.04</td>
<td>–</td>
<td>0.23 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>0.22 ± 0.03</td>
<td>0.55 ± 0.1</td>
<td>0.51 ± 0.11**</td>
</tr>
<tr>
<td>Rp (ml·mmHg⁻¹·s⁻¹)</td>
<td>Sham</td>
<td>2.1 ± 0.3</td>
<td>–</td>
<td>2.4 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>Banding</td>
<td>2.1 ± 0.4</td>
<td>3.9 ± 0.98</td>
<td>2.5 ± 0.5</td>
</tr>
</tbody>
</table>

The mean values (X ± SEM) are presented for the control animals (n = 7) and the banded animals (n = 7) for each parameter.  
Post-op: post operative, Zc: Characteristic impedance, Rp: peripheral resistance.  
* p < 0.05. Comparison between the Sham Operated Group and the Banding Group.  
† p < 0.001. Comparison between the Sham Operated Group and the Banding Group.  
‡ p < 0.05. Comparison between the “after instrumentation” (before Banding state) column and the “2nd post-operative day” column of the Banding Group.  
§ p < 0.001. Comparison between the “after instrumentation” (before Banding state) column and the “2nd post-operative day” column of the Banding Group.

post-operative day (Table 1). Specifically, in the Sham Group, on the day of instrumentation, arterial compliance was 0.54 ± 0.04 ml/mmHg, characteristic impedance was 0.21 ± 0.04 ml/(mmHg·s) and peripheral resistance was 2.1 ± 0.3 ml/(mmHg·s) (Table 1). On the 2nd post-operative day compliance was 0.51 ± 0.04 ml/mmHg, characteristic impedance was 0.23 ± 0.09 ml/(mmHg·s) and peripheral
resistance was $2.4 \pm 0.4 \text{ ml/(mmHg \cdot s)}$. After 2 days the arterial parameters of the sham operated animals were comparable and showed no significant differences.

Banding decreased compliance from $0.53 \pm 0.05$ to $0.18 \pm 0.03 \text{ ml/mmHg}$ after banding ($p < 0.001$) (Table 1). Even though compliance recovered slightly on the 2nd post-operative day ($2.27 \pm 0.03 \text{ ml/mmHg}$), the difference remained statistically significant when compared to the pre-banding state ($p < 0.001$).

Characteristic impedance, which is inversely related to the square root of aortic compliance, increased from $2.2 \pm 0.03 \text{ ml/(mmHg \cdot s)}$ to $5.5 \pm 0.1 \text{ ml/(mmHg \cdot s)}$ immediately following banding ($p < 0.05$) and remained constant thereafter. Peripheral arterial resistance increased from $2.1 \pm 0.4 \text{ ml/(mmHg \cdot s)}$ to $3.9 \pm 0.98 \text{ ml/(mmHg \cdot s)}$ following banding to return to pre-banding levels 2 days post operatively ($2.5 \pm 0.5 \text{ ml/(mmHg \cdot s)}$). However, these changes were not statistically significant ($p = 0.14$ and $p = 0.53$, respectively), possibly due to a large individual variability of resistance data (Table 1).

**Wave reflections**

Figure 3A shows an example of the aortic pressure wave as well as its forward and backward (reflected) wave components for the pre-banding, immediately following banding, and for the 2-day post-operative state. The data is from the same animal and heartbeat as those depicted in Figure 2.

In the Sham Operated Group the amplitudes of aortic pressure wave, the forward component and the backward (reflected) component were $21.4 \pm 1.5$, $22.5 \pm 1.7$ and $7.7 \pm 1.1 \text{ mmHg}$, respectively, and remained approximately the same on day 2 ($24.9 \pm 2.3$, $26.1 \pm 1.9$ and $8.9 \pm 0.9 \text{ mmHg}$, respectively). Furthermore, the amplitudes of the aortic pressure wave and its two components, after instrumentation and on the second post-operative day, did not differ to those of the pre-banding state in the Banding Group.

Figure 3B shows the comparison of the amplitude of the forward and backward wave components between the pre- and post-banding states. We found a significant increase in amplitude in both the forward and backward wave components in the banded animals. The amplitude of the forward wave increased from $25.2 \pm 2.2$ to $38.9 \pm 6.4 \text{ mmHg}$ immediately following banding ($p = 0.07$) and further to $49.2 \pm 11.3 \text{ mmHg}$ at 2 days post-operatively ($p < 0.05$). The amplitude of the backward wave increased from $8.5 \pm 1.1$ to $11.4 \pm 1.4 \text{ mmHg}$ following banding ($p = 0.16$) and to $23.4 \pm 5.4 \text{ mmHg}$ at 2 days post-operatively ($p < 0.05$).

Figure 3C shows the difference in the peak times of arrival ($\Delta t_p$) of the forward and backward pressure waves at the pre- and post-banding states. The $\Delta t_p$ is significantly decreased from $237.9 \pm 37.2$ to $152.5 \pm 24.8 \text{ ms}$ ($p < 0.05$) and is attributed to a significant shortening of the arrival time of the peak of the backward running wave component on the 2nd post-operative day. This signifies an earlier arrival of the reflected wave and relates to the appearance of the late systolic peak in the aortic pressure. The $\Delta t_p$ in the Sham Operated Group remained unaltered after the 2 day period ($245.3 \pm 39 \text{ ms}$ after instrumentation to $239.5 \pm 45 \text{ ms}$ on the 2nd post-op day; $p = 0.67$).

Figure 3D also shows the ratio of the amplitude of the backward to forward wave, as a simplified measure of the amount of reflection in the arterial system. The ratio did not change significantly, ranging from $0.34 \pm 0.04$ before banding to $0.35 \pm 0.08$ post-banding intra-operatively to $0.47 \pm 0.04$ at 2 days after banding ($p = 0.96$ and $p = 0.26$, respectively).

**Discussion**

We have performed an aortic banding procedure to reduce the proximal aortic compliance in a swine model. Banding of the proximal aorta yields a 50% reduction in total systemic arterial compliance. Short-term follow-up showed that the reduction in compliance leads to an increase in systolic pressure, pulse pressure and heart rate while peripheral resistance and cardiac output remain unaltered. Aortic pressure waves following the banding procedure have the characteristics of those found in patients with isolated systolic hypertension\(^\text{17}\) as well as in patients after aortic reconstruction surgery,\(^\text{18}\) with a pronounced late systolic peak. Since acute (day of instrumentation) and short-term (at 2 days post-op) effects of banding are found to be similar, we will discuss them together.

Previous studies, using various experimental models, have looked at the effects of reduced compliance on arterial hemodynamics.\(^\text{8,11,19-21}\) These studies reported a reduction in compliance ranging between 30 to 85%. All of these studies reported an increase in systolic and pulse pressure. The effects, however, on other hemodynamical parameters varied, apparently due to differences in the method and severity of compliance reduction.

Our study differs from the previously mentioned studies\(^\text{8,11,19-21}\) in that it does not only report on the acute effects of aortic banding but also 2 days post-operatively. Our measurements were done in closed chest, whereas some of the previous studies were performed in open chest preparations. Furthermore,
the method we applied to reduce compliance preserves the native aorta, without change in its geometry and the blood flow pathway. It has been reported that in an end-to-side graft anastomosis, decreased graft compliance leads to a substantial increase in the maximum anastomotic mean stress resulting in anastomotic intimal thickness. By banding the aorta in our experiment and not replacing it with a synthetic graft, aortic wall injury, changes in wall shear stress and flow disturbances at the suture sites were avoided.

We have chosen to reduce compliance by banding only the proximal aorta, leaving the rest of the arterial tree undisturbed. Arterial banding has been previously used. Okuh et al. applied this method in order to experimentally achieve acute compliance reduction in common iliac arteries of dogs to investigate if compliance mismatch is a stimulus for the development of neointimal hyperplasia. In a previous study, we found that compliance was reduced by 40% when the proximal descending aorta was blocked after inflation of an intra-aortic balloon, concluding that approximately 60% of total systemic compliance is contributed by the aorta located proximally to the occlusion. Inversely, our experiment focuses directly on the effect of compliance reduction on the proximal aorta. After
banding, total systemic compliance was reduced by approximately 50%. We thus provide good evidence that the proximal aorta is the major contributor to the total arterial compliance and is an important determinant of heart afterload.

Aortic banding yields a stiff aorta. This is clearly reflected by the increase in characteristic impedance of the aorta (Table 1). Since pulse wave velocity \( c \) is proportional to characteristic impedance \( (c = Z_c \cdot A / \rho) \), wave speed increases accordingly. This is substantiated by the reduction in the arrival time of the reflected waves, which in the presence of banding is reduced from 0.36 s pre-banding to 0.27 s two days post-operatively \( (p < 0.05) \) (Fig. 3).

The analysis of the aortic pressure wave into its forward and backward running components shows, however, that the increase in pulse pressure found after banding is not only attributed to the early arrival of the reflected wave, as is often simplistically assumed. In reality it is due to the combination of three events: an increase in the amplitude of the forward wave (Fig. 3B), an increase in the amplitude of the reflected wave (Fig. 3D), and a decrease in the arrival time of the reflected wave (Fig. 3C).

This also holds true for human data. Murgo et al. showed that in a Type A beat, typical of an old-aged person with reduced compliance and increased characteristic impedance, the amplitude of the forward pressure wave was approximately 30% higher than the forward pressure wave in a Type C beat, typical of a young healthy adult. Characteristic impedance is also 30% lower in the Type C beat, while flow is maintained. Therefore, the amplitude of the forward wave follows characteristic impedance as the theory predicts. The Type C beat morphology as described by Murgo et al. correlated with the pressure wave before banding, whereas the Type A beat with the pressure wave after banding (Fig. 2). The ratio of amplitudes of the reflected to forward running pressure waves remained unaffected after banding (Fig. 3D). Thus, the increase in the amplitude of the reflected wave post-banding is attributed primarily to the increase in the amplitude of the forward waves and not to an increase in the reflection coefficient.

Finally, in normal (non- or pre-banding) conditions, the reflected wave arrives during early diastole, just after closure of the aortic valve (Fig. 3A), thus enhancing coronary perfusion, which is mainly performed during this phase. After banding, the reflected wave arrives in early or mid systole, contributing to the increase in pulse pressure and potentially reducing coronary perfusion. We thus conclude that the increase in pulse pressure after a decrease in proximal aortic compliance results from an increased forward and reflected wave as well as from an earlier return of the reflected wave.

Total arterial compliance and peripheral vascular resistance are the major physiological parameters characterising cardiac afterload. The aorta is a compliant vessel and acts as an elastic reservoir. It absorbs part of the hydraulic energy imparted to the blood during systole to be released later during diastole thus converting the pulsatile flow from the heart into a more steady flow in the arterial system, maintaining a constant distal flow. Replacing the aorta with a non-compliant vascular prosthesis changes the elastic properties of the arterial system, results in a loss of arterial distensibility and thereby interferes with the ventriculo-arterial coupling. Currently available prosthetic grafts are stiff and the differences between graft materials, at present, are small. It has been estimated that a woven Dacron graft is approximately 170 times stiffer than the natural aorta. The apparent stiffness of synthetic prostheses should theoretically make them less satisfactory as arterial replacements, both due to the loss of pulse energy resulting from impedance mismatch between the graft and artery and because compliance mismatch imposes excessive stresses at the suture lines with resulting intimal hyperplasia, suture fatigue or anastomotic aneurysms.

Although not explicitly studied in this experiment, the heart certainly interacts with the altered arterial system after banding and contributes to the new aortic and pressure waveforms. In an isolated heart preparation where venous return (preload), contractility and heart rate were controlled, Elzinga and Westerhof have shown that a decrease in compliance leads to a decrease in cardiac output and a decrease in diastolic pressure while systolic pressure increased little. These results were subsequently theoretically supported and explained by Stergiopulos et al. and Segers et al. In our study, in the intact animal and 2 days after the operation, systolic pressure increased while diastolic pressure and cardiac output remained unchanged. There are apparently compensatory mechanisms, acting through neural or hormonal control or possibly via changed cardiac filling, that are engaged to preserve cardiac output and maintain diastolic pressure and therefore coronary perfusion. Immediately after banding heart rate did not change but at 2 days post-operatively heart rate increased by 30% \( (p < 0.05) \). The increase in heart rate helps maintain cardiac output and limits the increase in pulse pressure by shortening the duration of the diastolic pressure drop.
Morita et al. showed that increased aortic characteristic impedance caused an increase in the tension-time index (TTI), a decrease in the diastolic pressure-time index (DPTI) and a decrease of their ratio DPTI/TTI, used to evaluate myocardial oxygen demand and supply. These changes are consistent with those found during an increased left ventricle work load. The energy to maintain a forward blood flow in the aorta is given by mean pressure generated by the left ventricle. From the concept that the pulsatile component of blood pressure loses energy during vascular pulsation, widened pulse pressure becomes a cause of energy loss for maintaining the forward blood flow. Therefore, the left ventricle must generate excessive energy to maintain cardiac output through an unchanged peripheral resistance. This results in an increase in left ventricle work, consequently leading to hypertrophy. As previously reported, the use of woven Dacron grafts for extra-anatomic aortic bypass procedures may result in left ventricular hypertrophy due to the significant systolic pressure increase from the loss of the natural aortic "Windkessel" property. Thus, an increase in characteristic impedance after arterial replacement with vascular prosthesis may be injurious to the heart and may lead to left ventricle hypertrophy.

It is well known that arterial compliance decreases while systolic pressure increases with age. Hyper-tension observed in advanced age has often been related to increased peripheral resistance. However, our results suggest that at least for this short term period, reduction in aortic compliance alone, without change in peripheral resistance, can produce significant systolic hypertension and increase in pulse pressure. This in itself is an interesting observation because it may suggest that the development of isolated systolic hypertension may be a result of the progressive degeneration and loss of compliance of the human aorta.

Aortic reconstructive surgery is predominately performed on elderly patients. Though these patients may already have stiffer aortas with reduced aortic compliance, further compliance reduction caused after graft implantation is expected to induce significant hemodynamical changes. Maeta et al. observed hemodynamic changes in a small series of patients after bypass surgery of the thoracic aorta even though these patients’ ages ranged between 48 and 60 years. How hemodynamics will be effected in patients with aortic prosthesis is still to be investigated.

In conclusion, about half of the total systemic arterial compliance is located in the proximal thoracic aorta. Arterial reconstruction of the proximal aorta with a non-compliant graft results in a significant decrease in systemic arterial compliance, which in turn results in a significant increase in systolic and pulse pressure. The subsequent increase in characteristic impedance may be injurious to the heart and may lead to left ventricle hypertrophy.

These observations may have important clinical implications due to the current liberal use of non-compliant grafts in endovascular or surgical reconstruction of the thoracic aorta. The development of more compliant prosthesis, which match the host artery compliance, is expected to reduce the hemodynamic changes induced after their implantation. Further experimental work is needed to focus on left ventricle response to long-term exposure to reduced aortic compliance (or increased characteristic impedance).

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